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LIFE CYCLE MANAGEMENT

Life cycle energy and environmental benefits of a US industrial symbiosis

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Abstract
Purpose The industrial ecosystem identified in and around the Campbell Industrial Park in Honolulu County, Hawai'i involves 11 facilities exchanging water, materials, and energy across an industrial cluster. This paper highlights the advantages of this arrangement using life cycle assessment to determine the energy and environmental costs and benefits of the existing pattern of exchanges.
Methods A consequential approach was used to evaluate each material substitution for four environmental impact categories: primary energy use, greenhouse gas (GHG) emissions, acidification, and eutrophication. Each material exchange included avoided production and reduced use of virgin materials, any necessary pre-processing or transportation of local by-products, and avoided treatment or disposal of these by-products.
Results and discussion All exchanges exhibited positive net savings across all environmental impact categories, with the exceptions of waste oil and tire-derived fuel burned as substitutes for coal. The greatest savings occur as a result of sharing steam between a combined cycle fuel oil-fired cogeneration plant and a nearby refinery. In total, the environmental savings realized by this industrial cluster are significant, equivalent to 25 % of the state's policy goal for reducing the industrial component of GHG emissions over the next decade. The role of policy in supporting material and energy exchanges is also discussed as the central cluster of two power plants and two refineries share steam and water in part under regulatory requirements.
Conclusions The results show environmental benefits of the sharing of by-product resources accrued on a life cycle basis, while for the local context, the reduction of imported fuels and materials helps to reduce the external dependency of Oahu's remote island economy. The environmental benefits of materials exchanges are often ignored in energy policy, though, as in this case, they can represent considerable savings.

Keywords By-product exchange · Environmental co-benefits · Hawaii · Industrial ecology · Industrial symbiosis · Life cycle assessment

1 Introduction

One innovative but often hidden approach to increasing resource conservation and efficiency in business is that of industrial symbiosis, where firms in proximity share material, water, and energy by-products, as one company's waste becomes another company's feedstock. This arrangement can be hidden in the sense that companies will voluntarily exchange materials if there is an economic rationale, but there often is little awareness by others of this arrangement, and the companies themselves may not realize and take credit for the environmental benefits of doing so. While the early literature in this area argued that these sorts of arrangements were likely to be advantageous for participating firms (Côté and Cohen-Rosenthal 1998), more recent research from across the world has shown the actual economic and environmental benefits of industrial symbiosis in Europe (Baas and Boons 2004; Sokka et al. 2011; Jacobsen 2006), Asia (Shi et al. 2010; Chen et al. 2011; Tian et al. 2013; van Berkel et al. 2009; Lin et al. 2012), Australia (van Beers et al. 2007), and North America (Chertow and Lombardi 2005). Case studies of industrial symbiosis such

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as these generally highlight advantageous cascades of by-product energy, reduction in transport distances, or substitutions of secondary materials for virgin materials. In this paper, we use life cycle assessment (LCA) to understand and contextualize the environmental benefits of symbiotic activities, using a well-documented industrial cluster in Honolulu, Hawai'i (Chertow and Miyata 2011). This is a particularly interesting case given Oahu's remote location and the potential role of the symbiosis in increasing the resilience of the island's physical economy (Eckelman and Chertow 2009b; Fiksel 2003).

The Campbell Industrial Park, created in 1958, is the only heavy industry site in Hawai'i, located in the southwest of the densely populated island of Oahu. It is also the largest industrial park in the State of Hawai'i, with approximately 250 companies. A core group of these companies have self-organized to form what we are calling the Campbell Industrial Symbiosis, a resource or by-product exchange network, anchored by the only coal-fired plant on Oahu, owned by AES Corporation, which generates approximately 180 MW and 30,000 pph (pounds per hour, or 330 GJ annually) of steam. Filling out the core of the cluster along with the coal plant are the oil-fired Kalaeloa cogeneration plant (210 MW), and two large oil refineries owned by Chevron and Tesoro, respectively. These oil refineries operate small (~9 MW) cogeneration plants and steam boilers. Also participating at the time of study were a cement company, a private construction and demolition (C&D) waste landfill, the municipal water authority, an oil and tire recovery company, a wastewater treatment plant, a biosolids benefication company, and a local golf course. Figure 1 depicts the symbiosis among 11 companies as of the late 2000s and is organized to highlight the major materials being exchanged: various grades of water and steam; unconventional fuels such as granular activated carbon (GAC), waste oil, and shredded tires; ash; and sewage sludge (biosolids).

2 Methods

LCA often examines goods and services produced or delivered individually or as general categories, while burdens associated with any coproducts or by-products accompanying the reference flow of interest are assigned using allocation and/or system expansion methods. The application of LCA to a mixed-sector industrial system that simultaneously produces numerous salable products as with the described here presents several methodological issues discussed below.

2.1 Functional unit

First, an LCA must define a functional unit as the basis of comparative environmental analysis, for example, an assessment of different transportation systems may choose as a functional unit one passenger-kilometer travelled. As with previous LCA studies of industrial symbiosis (Chertow and Lombardi 2005; Sokka et al. 2011), a complex functional unit was chosen as the production or physical output of all 11 enterprises based on exchanged materials and energy, which allows for consideration of all by-products, waste, and raw materials, and which matches the traditional unit of

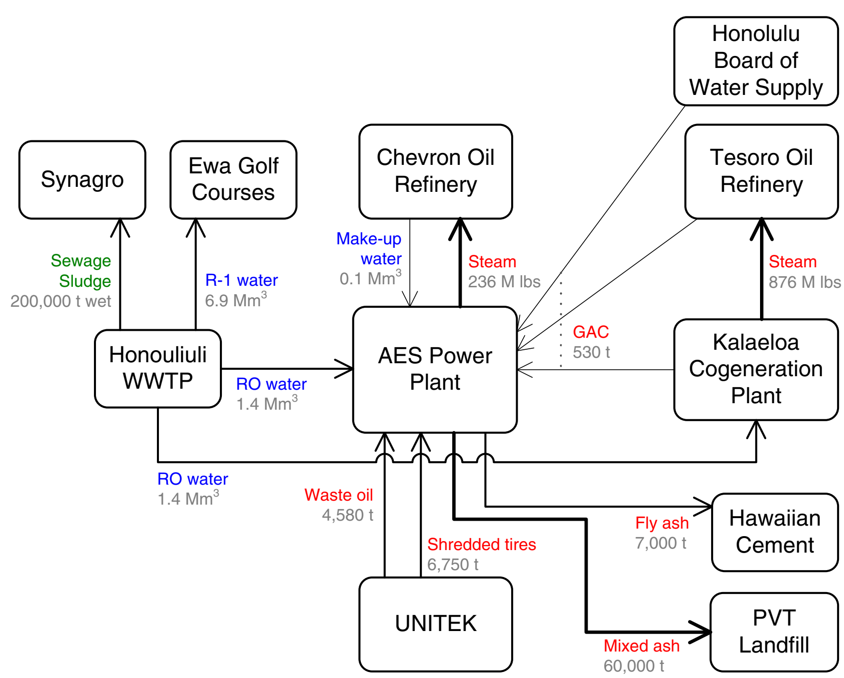

Fig. 1 Material flows within the Campbell Industrial Symbiosis. Notes: *RO* reverse osmosis; *GAC* granular activated carbon

analysis in industrial symbiosis. (This choice also locks in the structure of the cluster in terms of relative output of each individual firm, a disadvantage that is discussed in more detail below). With this fixed functional unit, the environmental burdens associated with the existing symbiotic arrangement are compared to those of a hypothetical (but more common) arrangement that would exist without the symbiosis. This assessment explicitly includes waste management activities for each major category of exchanged materials.

2.2 Data collection

The material and energy exchange data were collected from the companies themselves during 2005–2006 with several rounds of follow-up in 2008 and 2009, and the analysis and results presented here reflect the Campbell Industrial Symbiosis as it existed circa 2010. In attempting to isolate the environmental costs and benefits of by-product material and energy exchanges, this comparative assessment was conducted on a relative basis only. Therefore, the results do not reflect the absolute quantities of resource inputs or emissions from the industrial cluster as a whole, but rather show the net environmental impacts of the symbiosis versus a situation without exchanges of materials and energy.

Raw material and energy inputs and emissions collected directly from each facility were then assembled into a life cycle inventory. Hawai'i-specific factors were used as much as possible; where specific information was not available, records from national or international life cycle inventory databases were used, as noted in Table 1. As the industrial symbiosis is based around a core of power generation facilities and refineries, fossil fuel combustion for electricity and heat is a crucial component of the analysis. Emission factors for the specific power plants in question were gathered from facility information within the eGRID database of the US EPA (2012), which tracks operating parameters and emissions of CO_2, SO_2, NO_x, and mercury for every power plant in the USA, including the on-site cogeneration plants at the Chevron and Tesoro refineries. eGRID provides information on a heat input basis; in order to convert to a mass input basis, a heat content of 22.4 MMBtu/short ton (26 MJ/kg) was assumed for coal used in Hawai'i (US EIA 2012). For some processes, such as tire shredding, electricity is the main energy input. LCI data for electricity use vary widely from place to place, based on the parameters such as the generation mix, combustion efficiency, and pollution controls (Eckelman et al. 2008; Weber et al. 2010; Siler-Evans et al. 2012). Oahu and the other Hawaiian islands operate their own individual microgrids, which are currently isolated from each other. Using eGRID data specific to the Oahu microgrid, called HICC Oahu, unit emission factors per kilowatt hour were calculated for local electricity use (US EPA 2012). Transportation impacts were only considered for shipping to and from Oahu, both for imports, such as coal, and exports, such as used tires. In cases where a material exchange both avoids and additionally requires local transport, such as bringing ash to Hawaiian Cement instead of to the landfill, distances are assumed to be approximately equivalent.

2.3 System expansion

The present study employs system expansion to estimate the environmental impacts that result from each bilateral exchange of material, using for comparison the performance of the symbiosis in the absence of the exchange. Some processes are directly avoided by using by-product materials and energy, particularly those related to material production and transport, but in some cases additional processes are required to achieve functional equivalence, particularly for processing of by-products prior to use as feedstock materials. For example, in the case of shredded tire use at AES, disposal of the tires and the production, transport, and combustion of the substituted coal are avoided, but there are additional impacts from the shredding of the tires and their combustion.

In many cases, backup sources of materials and/or energy have already been identified by the firms in question as a risk management measure. So, in this analysis, treating and transporting the exchanged by-products for use as industrial feedstocks is compared to sourcing equivalent material from alternate suppliers. This framework mirrors the financial modeling that symbiotic firms undergo when setting up contracts, as by-product exchanges among facilities in the USA are most often the product of business decisions rather than regulatory requirements, with a clear understanding of costs both with and without these exchanges. Allocation of waste management inputs and emissions was avoided as both the generator and the ultimate user of the by-product were both included in the system in every case. Figure 2 shows a diagram of the symbiosis, with the system expanded to include all of the avoided processes. In all cases, the net impacts for each exchange were considered; these impacts can be positive or negative.

The greatest challenge in performing system expansion in this study was in determining what would most likely happen to the by-product materials in the absence of the symbiosis and the type and quantities of materials that would be required in their place. On Oahu, regulations from the state of Hawai'i and the city and county of Honolulu restrict certain types of disposal and in some cases specify how a material must be handled. Most types of materials that are exchanged within the Campbell Industrial Symbiosis exist in significant

Table 1 Unit characterization factors for material and energy substitutions at the Campbell Industrial Symbiosis

Material	Annual amount	Avoided or (additional) process	Primary energy GJ/t	Life cycle emissions		
				Greenhouse kg CO_2e/t	Acidifying mol H^+/t	Eutrophying kg N/t
Mixed ash	60,000 t	Ash disposal[a]	0.3	9.55	3.57	0.001
Substitutes for: sand	50,000 t	Sand extraction[a]	0.03	2.39	1.00	0.001
Fly ash	7,000 t	Ash disposal[a]	0.3	9.55	3.57	0.001
Substitutes for: Portland cement	7,000 t	Cement production[b]	2.7	761	67.8	0.161
		Cement transport[a]	0.6	40.1	47.6	0.091
Sludge (95 % wet)	200,000 t	Sludge landfill disposal[a, c]	0.32	646	7.65	0.934
Substitutes for: fertilizer	2,500 t	Fertilizer production[a]	36.0	2,610	2,140	11.7
		Fertilizer transport[a]	0.6	40.1	47.6	0.091
RO wastewater	2.8 Mm^3	–	–	–	–	–
Substitutes for: demineralized water	2.8 Mm^3	Water softening and distribution[a]	0.009	0.79	0.19	0.005
Condensate water	0.1 Mm^3	–	–	–	–	–
Substitutes for: demineralized water	0.1 Mm^3	Water softening and distribution[a]	0.002	0.79	0.19	0.005
R-1 water	6.9 Mm^3	RO water treatment[a]				
Substitutes for: groundwater	6.9 Mm^3	Groundwater extraction, treatment, distribution[a]	0.002	0.16	0.04	0.001
Steam (AES)	236 M lbs	–	–	–	–	–
Substitutes for: steam (Chevron)	236 M lbs	Steam production[a, d]	0.001	0.05	0.002	<0.001
Steam (Kalaeloa)	876 M lbs	Steam production[d, e]	0.002	0.13	0.019	<0.001
Substitutes for: steam (Tesoro)	876 M lbs	Steam production[a, d]	0.002	0.10	0.014	<0.001
Tire-derived fuel	6,750 t	Tire disposal[a]	0.9	52.3	52.5	0.120
	6,750 t	(Tire shredding)[e, f]	5.3	380	39.3	0.025
	6,750 t	(Tire combustion)[a]	0.5	3,140	23.6	0.029
GAC	530 t	Landfill disposal[a]	0.4	14.6	2.98	0.024
	530 t	(GAC combustion)	0.3	2,340	30.5	0.042
Waste oil	3,210 t	Oil disposal[g, h]	0.4	3,890	179	0.054
	1,370 t	Oil re-refining[g, h]	37.3	577	34.6	0.06
	4,580 t	(Oil combustion)[g, h, i]	0.4	3,890	35.8	0.016
Substitutes for: coal	17,970 t	Coal production[b]	26.9	18.5	1.96	0.001
	17,970 t	Coal transport[a]	0.6	40.1	47.6	0.091
	17,970 t	Coal combustion[e]	—	2,271	39.7	0.045

SI units except where noted

[a] Ecoinvent (2010)

[b] NREL (2012)

[c] Accounts for methane capture and flaring at the Waimanalo Gulch Sanitary Landfill

[d] Per pound of steam

[e] US EPA (2012)

[f] Sousa et al. (2001)

[g] US EPA (2009)

[h] Boughton and Horvath (2004)

[i] Accounts for existing pollution controls at the AES Power Plant

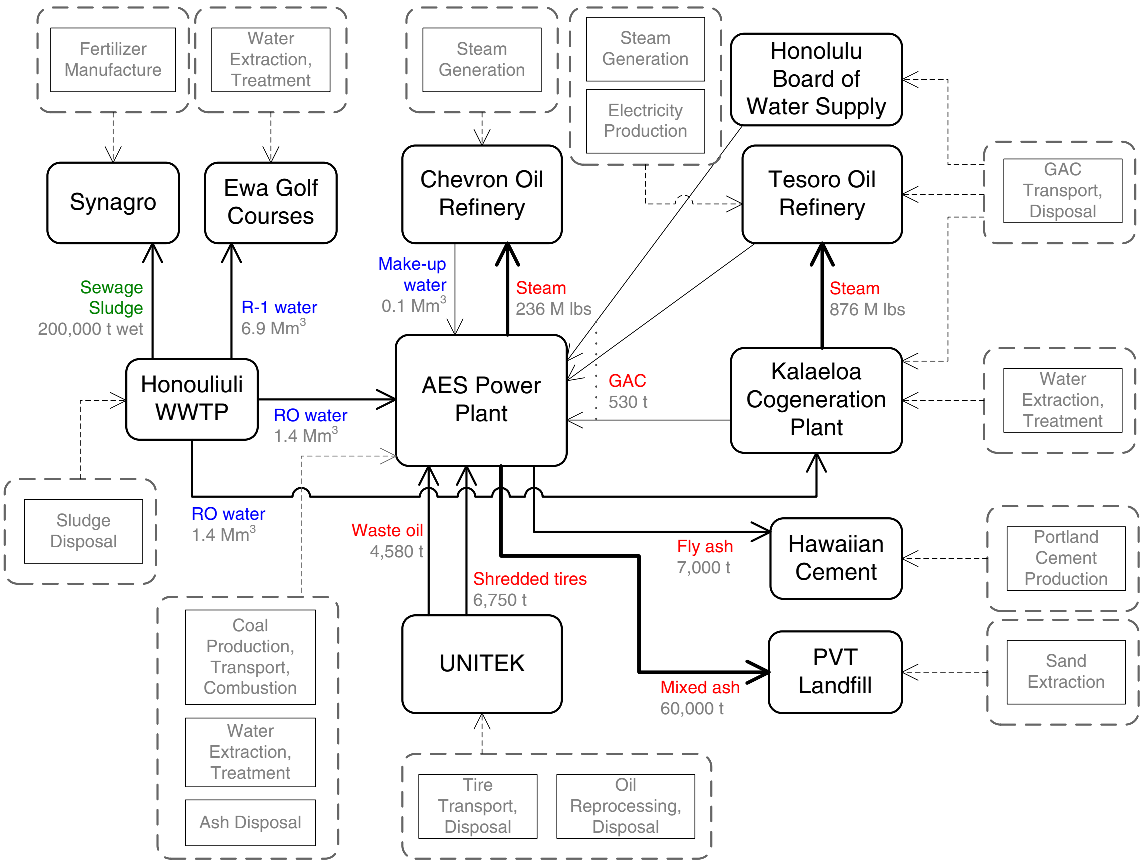

Fig. 2 Full system boundary of the Campbell Industrial Symbiosis. Notes: *RO* reverse osmosis; *GAC* granular activated carbon

quantities elsewhere on the island, so it was simple enough to track how these waste categories are typically handled and to assume that the same disposal routes would apply to the exchanged material in the absence of the symbiosis. For purposes of this analysis, the following are the reuse options considered in the event that the existing symbiotic exchanges were no longer available:

- Bottom ash: Enters ash monofill section of Waimanalo Gulch Sanitary Landfill
- Fly ash: Enters ash monofill section of Waimanalo Gulch Sanitary Landfill
- Sewage sludge: Enters Waimanalo Gulch Sanitary Landfill
- Water: Treated wastewater is discharged via pipeline to the ocean
- Steam: Excess heat from AES and Kalaeloa generation plants is purged through the use of standard utility cooling towers
- Old tires: Restricted from the landfill, shipped off-island for landfill disposal on the mainland USA
- Granular activated carbon: Restricted from the landfill, shipped off-island for treatment and impoundment on the mainland USA
- Waste oil: Restricted from sewer disposal, either reprocessed for engine oil (30 %) or incinerated on the island (70 %)

2.4 Impact assessment

Four environmental impact categories were considered: primary energy use, greenhouse gas emissions (CO_2e, using GWP_{100} factors), acidification (H^+ equivalents), and eutrophication (N equivalents), with characterization factors from the US EPA's TRACI 2 model (Bare 2011). Inventory data were gathered from the ecoinvent database and a number of US government sources. Positive and negative impacts were tabulated for each unit process individually in a spreadsheet model.

Table 1 shows the impact factors for each process per unit of material as a combination of unit LCI data and the TRACI characterization factors. Both avoided and additional (in parentheses) processes are shown. These characterization factors are simply multiplied by the quantity of the material (either by-product or substituted material) or energy flows in question, with the products summed across all flows in order to quantify the total impacts or benefits of a material exchange.

There are other impact categories that would be particularly relevant for Hawai'i, particularly around land use and biodiversity impacts; however, no local characterization factors have been developed and, given the unique geological and ecological characteristics of Hawai'i, it

would not be appropriate to utilize factors for these impact categories that have been developed for other (mostly continental) locations.

3 Results

Figure 3(a–d) depict the aggregated costs and benefits of each major material substitution for each of the four environmental impact categories. It is clear that many exchanges carry environmental costs but that, with two exceptions, these costs are less than the benefits of the symbiotic exchange. For example, the use of tire-derived fuel (TDF) as a substitute for coal results in 39 TJ of additional energy use for tire shredding and TDF combustion (see Fig. 3(a)), but this is more than offset by the 266 TJ of energy savings from avoided coal production, transport, and combustion, as well as avoided disposal of tires in the mainland USA.

The one exception where environmental costs exceed benefits relate to the use of alternative fuels as substitutes for coal at the AES plant. In the first case, greenhouse gas (GHG) emissions with and without the use of TDF are roughly equal; their sum is slightly negative (see Fig. 3(b)). The primary reason for this is the relatively high emissions factor for TDF of 3,137 kg CO_2e per ton TDF combusted, compared to 2,271 kg CO_2e per ton of coal (see Table 1), while the heat content of TDF is nearly 30 % higher than that of coal at the plant. Burning waste oil as a substitute for coal at the AES power plant currently results in reduced acidification impacts (see Fig. 3(c)), as the waste oil has a lower average sulfur content (0.3 %) (Boughton and Horvath 2004) than the AES coal (0.6 %) (NETL 2007) had in 2007. (As of 2010, AES imports its coal through a long-term contract with an Indonesian supplier, with a maximum sulfur content specification of 1.5 %; using this factor would further increase the acidification benefits of the substitution of waste oil for coal.) If high-sulfur waste oils were collected and incinerated, however, these acidification benefits would likely be reversed due to increased SO_2 emissions.

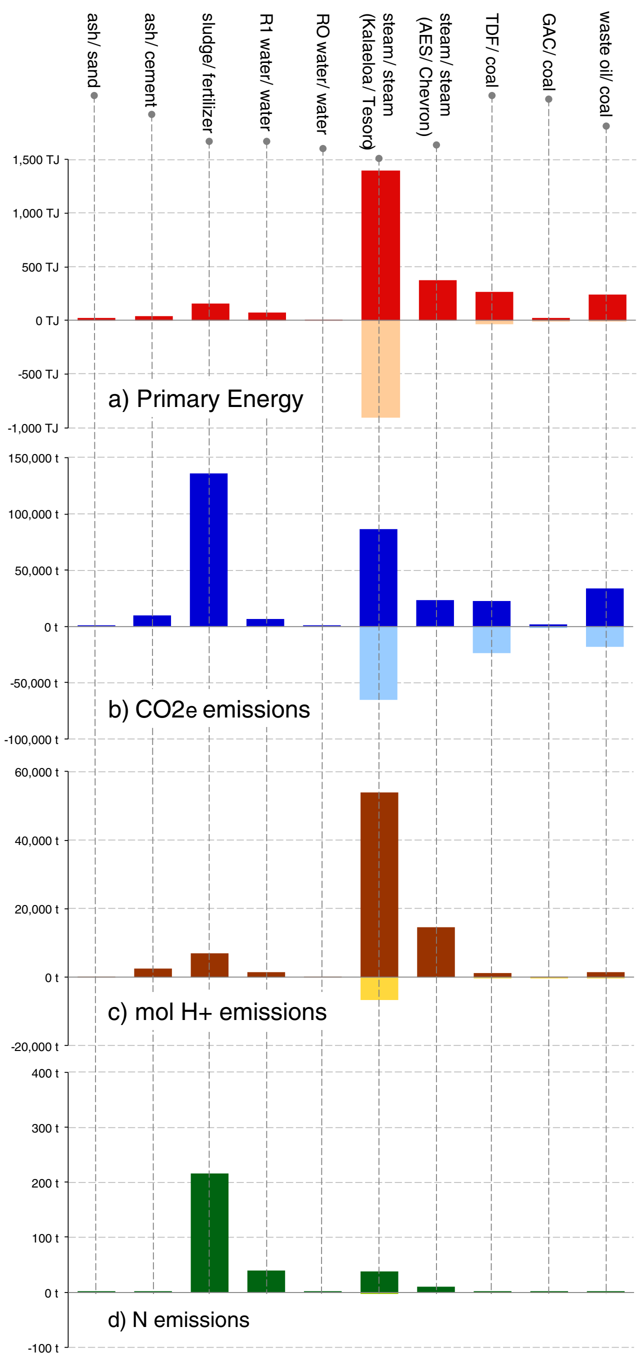

Fig. 3 *a–d* Positive (*above each x-axis*) and negative (*below*) environmental impacts of each exchange

4 Discussion

The pattern of relative environmental performance for the different material exchanges is similar among the four impact categories, with some notable deviations. The processing of sewage sludge into fertilizer pellets results in significant GHG emissions reductions from avoided landfill decomposition, but in the case of acidification and eutrophication, these benefits primarily come from avoided fertilizer production. Considering water use, both types (RO and R-1) are shared in quite large quantities, but as the unit environmental costs of treating and distributing water are so small, the total impacts are not significant when compared to the other exchanges. The substitution of alternate fuels for coal at AES is particularly important for GHG emissions relative to SO_2 and NO_x emissions, as these latter emissions are partially mitigated by pollution control equipment.

4.1 Steam exchanges

The largest impacts consistently come from the exchange of steam between the power plants and the refineries, consistent

with other studies that have found substantial life cycle benefits from steam exchanges within industrial clusters (Lin et al. 2012; Chertow and Lombardi 2005). These results are worth discussing in detail. As seen in Table 1, the emissions factors for steam produced at AES and Kalaeloa power plants are lower than those for the Chevron and Tesoro refineries, respectively. Each of the four facilities coproduces both electricity and steam, but the process configurations are different.

Using a consequential approach (Ekvall and Weidema 2004), the counterfactual question is, ‘in the absence of the exchange, what would happen to the generated steam at the donor facilities and how would steam otherwise be produced at the receiving facilities?’ In the case of AES, steam is generated for electricity generation but would afterwards be considered a true by-product with zero value to the power plant, and under an economic allocation scheme would be essentially emissions free. The two refineries both operate boilers and cogeneration plants. In these cases, the steam is used on-site in the refining process, and so the steam has a technical purpose and thus would receive some portion of the cogeneration combustion emissions under allocation or system expansion. On the other hand, the Kalaeloa facility is a combined cycle plant where exchanged steam is pulled off after the gas turbine but before the steam turbine, meaning that the quantity of steam produced is dependent on the amount of fuel used (and therefore on the electricity produced in the first turbine) but also affects the total amount of electricity produced. In this configuration, a decrease in demand for steam means that more electric power can be generated. Given that this LCA examines substitution via system expansion (in this case, steam for steam), it is critical that the analysis be performed consistently for the two cases.

Our approach was to rely on the fixed functional unit of the total physical output of the industrial cluster. The primary products of the refineries are petroleum distillates, while the primary product of the power plants is electricity. For the AES–Chevron exchange, by-product steam from coal combustion is substituting for steam from boilers and cogeneration plants. The cogeneration plants are burning refinery gas and naphtha, the feed rates of which are proportional to the constant functional unit, and thus these plants will generate a fixed amount of electricity and steam regardless of the steam being exchanged. Steam from AES will then only displace that from Chevron's fuel oil boilers, which run on a mix of refinery gas and low-sulfur fuel oil. Again, the availability of refinery gas is constant with the functional unit, and so AES steam must displace steam from fuel oil boilers. For the Kalaeloa–Tesoro exchange, combined cycle cogenerated steam is substituting for fuel oil boilers (in this case a much larger portion of the refinery steam demands are satisfied). Under system expansion, the production of Kalaeloa steam results in avoided electricity production, but only through the steam turbine. Avoided electricity output can be calculated by assuming a thermal efficiency of 30 % for the Rankine steam cycle portion of the combined cycle plant, which is the method used here. It can also be estimated by isolating the efficiency of electricity generation without steam, or the electric efficiency of the combined heat and power plant (Maruyama and Eckelman 2009).

4.2 Sector averages and market effects

It is useful to discuss the methods used here in relation to a recent paper by Mattila et al. (2012) that gives guidance about applying LCA to quantifying the environmental trade-offs associated with industrial symbiosis. These authors rightly point out several disadvantages of using system expansion, including the difficulty of making robust assumptions for alternate reuse or disposal options for exchanged materials, and the fact that without the exchanges, facilities running with a certain configuration or set of technologies may cease to be economically competitive and close as a result, making for a tenuous comparison. (Of course, this can and does occur to firms within industrial symbioses as well.) Rather than compare the symbiosis to a disconnected network of the exact same firms using the same technologies, the authors suggest that it is more realistic to compare with sector average production for each primary industrial product, using environmentally extended input–output techniques. This may well be the case for industrial clusters that are more integrated into the global economy, with firms that sell into large national or international markets. In this case study, however, most of the products of the Campbell industrial symbiosis are used on Oahu or nearby islands and the cluster itself represents a fairly large portion of the island's industrial output, so that system expansion using local material, energy, and waste management attributes is the more tractable option.

On a related point, Mattila et al. (2012) also discuss the importance of scale and the effects that decisions made by the industrial symbiosis actors might have on local markets, particularly when carrying out a consequential LCA. This may be an important consideration in the present study given the moderate size of the physical economy of Oahu, although the analysis does not account for such market fluctuations or induced changes in the economic structure of the island. For example, in our analysis, mixed ash that currently substitutes for sand at the private landfill is assumed to go to an ash monofill otherwise, with local sand or soils being used in its place. Because the mass involved is fairly large (60,000 t), this would likely change the local price of sand, perhaps inducing additional production and transport, which should be taken into account in a full consequential analysis.

4.3 Regulatory and permitting determinants

There is another point that is important to discuss in the choice between attributional and consequential LCA, which is the fact that the operating permits for the two power plants mandate co-production of steam, up to 5 % of total energy output. Similarly, the municipal wastewater authority is under a federal consent decree to recycle some of its sewage sludge, which in part prompted its cooperation with Synagro. We made the case earlier that these symbiotic exchanges are generally the result of business decisions with a suite of available options for procuring input materials and energy. The environmental costs and benefits that resulted from the symbiosis are the product of a laissez-faire arrangement in that the companies were not coerced to join together; rather, each found the other for reasons of economic efficiency in a self-organized fashion without any special recognition or broad awareness of the other exchanges (Chertow and Miyata 2011). Regulatory requirements to coproduce or engage in industrial waste recycling might suggest an attributional approach in considering these facilities. This choice is crucial as comparative assessments of these two methods for the same system have been performed elsewhere showing quantitative and qualitative differences in results (Thomassen et al. 2008).

4.4 Contribution to policy goals

Finally, it is necessary to understand these results in the context of the local environmental situation and prevailing policy. In previous work, we have shown that industrial symbiosis and, more generally, industrial waste reuse can represent significant energy savings and GHG reductions when considered on a statewide basis (Eckelman and Chertow 2009a). In Hawai'i, two major policy goals are the reduction of GHG emissions to 1990 levels by 2020 and the sourcing of renewable energy for 70 % of the state's electricity supply by 2030 (the Hawai'i Clean Energy Initiative). Practically speaking, this means that the state will aim to reduce GHG emissions by 800,000 t CO_2e, when just considering emissions from industry and power generation. The total savings from the Campbell industrial symbiosis amount to approximately 200,000 t CO_2e or 25 % of the reduction goal for industry, primarily from the use of AES steam in the Chevron refinery. This result supports the argument that promoting symbiotic activities can lead to regionally significant environmental savings and help to achieve challenging policy goals around energy use and air emissions.

5 Conclusions

The results of this case study clearly show that local exchanges of materials and energy among clustered industrial facilities can lead to environmental savings on a life cycle basis, corroborating findings from similar sites around the world. The use of by-product materials is not a priori environmentally beneficial, as they can in principle carry larger burdens than functionally equivalent virgin materials due to the need to collect, process, and otherwise beneficiate the by-products. The application of LCA to the Campbell Industrial Symbiosis shows that the environmental benefits are positive for all impact categories and all exchanges, save for one type of alternate fuel. The absolute values of these benefits are also important in showing how industrial symbiosis within a single industrial cluster can, on its own, represent significant progress toward a statewide GHG policy goal.

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